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Dated: 11/22/05 Signature: Georgina Matos (Georgina Matos)

O I P E NOV 22 2005 PATENT & TRADEMARK OFFICE

Docket No.: 299002051800
Client Ref. No.: F5-0036823/00R00553-1/US
(PATENT)

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:
Yoshihiro UETA et al.

Application No.: 09/759,312 | Confirmation No.: 1784

Filed: January 12, 2001 | Art Unit: 2812

For: NITRIDE COMPOUND SEMICONDUCTOR LIGHT EMITTING DEVICE AND METHOD FOR PRODUCING THE SAME | Examiner: S. Mulpuri

APPELLANT'S BRIEF

Mail Stop Appeal Brief - Patents
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

11/28/2005 DTESSEM1 00000049 031952 09759312
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Dear Sir:

This brief is in furtherance of the Notice of Appeal, filed in this case on September 23, 2005.

The fees required under § 1.17(f), and any required petition for extension of time for filing this brief and fees therefore, are dealt with in the accompanying TRANSMITTAL OF APPEAL BRIEF.

This brief contains items under the following headings as required by 37 C.F.R. § 1.192 and M.P.E.P. § 1206:

I. Real Party in Interest
II Related Appeals and Interferences
III. Status of Claims
IV. Status of Amendments
V. Summary of Claimed Subject Matter
VI. Grounds of Rejection to be reviewed on Appeal
VII. Arguments
VIII. Claims Appendix

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PTO/SB/21 (09-04)
Approved for use through 07/31/2006. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

TRANSMITTAL FORM

(to be used for all correspondence after initial filing)

Application Number	09/759,312
Filing Date	January 12, 2001
First Named Inventor	Yoshihiro UETA
Art Unit	2812
Examiner Name	S. Mulpuri
Attorney Docket Number	299002051800
Total Number of Pages in This Submission	101

ENCLOSURES (*Check all that apply*)

- [x] Fee Transmittal Form + duplicate for fee processing (2 pages)
  - [ ] Fee Attached
- [ ] Amendment/Reply
  - [ ] After Final
  - [ ] Affidavits/declaration(s)
- [ ] Extension of Time Request
- [ ] Express Abandonment Request
- [ ] Information Disclosure Statement
- [ ] Certified Copy of Priority Document(s)
- [ ] Reply to Missing Parts/ Incomplete Application
  - [ ] Reply to Missing Parts under 37 CFR 1.52 or 1.53
- [ ] Drawing(s)
- [ ] Licensing-related Papers
- [ ] Petition
- [ ] Petition to Convert to a Provisional Application
- [ ] Power of Attorney, Revocation Change of Correspondence Address
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- [ ] CD, Number of CD(s) ______
  - [ ] Landscape Table on CD
- [ ] After Allowance Communication to TC
- [ ] Appeal Communication to Board of Appeals and Interferences
- [x] Appeal Communication to TC (18 pages) **(Appeal Notice, Brief, Reply Brief)**
- [ ] Proprietary Information
- [ ] Status Letter
- [x] Other Enclosure(s) (please Identify below):
  1. Appendix A (3 pages inc. divider)
  2. Appendix B (7 pages inc. divider)
  3. Appendix C (36 pages inc. divider)
  4. Appendix D (30 pages inc. divider)
  5. Appendix E (4 pages inc. divider)
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Remarks

SIGNATURE OF APPLICANT, ATTORNEY, OR AGENT

Firm Name	MORRISON & FOERSTER LLP (Customer No. 25226)		
Signature	*[signature]*		
Printed name	Michael S. Garrabrants		
Date	11/22/05	Reg. No.	51,230

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Dated: Signature: *Georgina Matos* (Georgina Matos)

pa-1027303

IX. Evidence Appendix
X. Related Proceedings Appendix

I. REAL PARTY IN INTEREST

The real party in interest for this appeal is:

Sharp Kabushiki Kaisha

II. RELATED APPEALS AND INTERFERENCES

There are no other appeals or interferences which will directly affect or be directly affected by or have a bearing on the Board's decision in this appeal.

III. STATUS OF CLAIMS

A. Total Number of Claims in Application

There are sixteen claims pending in this application.

B. Current Status of Claims

1. Claims canceled: 2, 5, and 16
2. Claims withdrawn from consideration but not canceled: 8-11
3. Claims pending: 1, 3, 4, 6, 7, 12-15, and 17-19
4. Claims allowed: none
5. Claims rejected: 1, 3, 4, 6, 7, 12-15, and 17-19.

Claims On Appeal

The claims on appeal are claims 1, 3, 4, 6, 7, 12-15, and 17-19

IV. STATUS OF AMENDMENTS

Applicant filed an Amendment After Final Rejection on July 25, 2005. The Examiner responded to the Amendment After Final Rejection in an Advisory Action mailed August 16, 2005. In the Advisory Action, the Examiner indicated that claims 1, 3-4, 6-7 and 12-19, are rejected.

The claims in the Claims Appendix incorporate the amendments indicated in the paper filed by Applicant on December 28, 2004. No claim amendments have been made since that date.

V. SUMMARY OF CLAIMED SUBJECT MATTER

The claimed inventions are directed generally to nitride compound semiconductor light emitting devices, and methods for production thereof. In an example, the invention includes a GaN substrate having a (0001) plane tilted away from a <0001> direction by an angle between 0.05 degrees and less than 2.0 degrees. (*see e.g.*, Page 7, Line 24 – Page 8 Line 5; Page 23, Lines 2-6; Page 15, Line 24 – Page 16, Line 10; Figure 3). (0001) planes in GaN are planes containing Gallium nuclei, and may be readily contrasted with (000-1) planes containing Nitrogen nuclei. (*see* Zauner Abstract).

The invention further includes a multilayer semiconductor structure. The multilayer structure includes an n-type layer containing a nitride compound semiconductor, an active layer containing a nitride compound semiconductor, and an acceptor doping layer comprising $Ga_xIn_yAl_{1-(x+y)}N$ (where $0 \leq x \leq 1$; $0 \leq y \leq 1$; and $0 \leq x+y \leq 1$) (*see* page 7, line 23- page 8, line 9). In present aspects, the GaN substrate and the active layer are formed so that they are separated from each other by at least about 1μm.

Independent claim 1 is directed to a nitride compound semiconductor light emitting device, comprising, "a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is less than 2°" (*see e.g.*, page 20, lines 1-8), "a n-type layer containing a nitride compound semiconductor located above the GaN substrate" (*see e.g.*, n-GaN layer 103 illustrated in FIG. 1A and described at page 20, line 10), "an active layer containing a nitride compound semiconductor located above the GaN substrate (*see e.g*, page 21, lines 1-15 describing active layer 106), and "an acceptor doping layer containing a nitride compound semiconductor comprising $Ga_xIn_yAl_{1-(x+y)}N$ (where $0 \leq x \leq 1$; $0 \leq y \leq 1$; and $0 \leq x+y \leq 1$) located above the GaN substrate" (*see e.g.*, claim 2 as originally filed). The GaN substrate and the active layer are formed so as to be apart from each other by a distance which is equal to or greater than about 1μm (*see e.g.*, page 31, line 8-15).

Independent claim 14 is to a nitride compound semiconductor light emitting device comprising, "a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is less than 2°, "a n-

type layer containing a nitride compound semiconductor located above the GaN substrate", "an active layer containing a nitride compound semiconductor located above the GaN substrate", "an acceptor doping layer containing a nitride compound semiconductor comprising $Ga_xIn_yAl_{1-(x+y)}N$ (where $0 \leq x \leq 1$; $0 \leq y \leq 1$; and $0 \leq x+y \leq 1$) located above the GaN substrate, wherein the acceptor doping layer exhibits a p-type conductivity as grown." (*see e.g.*, page 31, lines 1-6).

Claim 3, which depends from claim 1, and claim 15 which depends from claim 14, recite that the GaN substrate has a crystal orientation which is tilted away from a <0001> direction in a <11-20> or <1-100> direction (*see e.g.*, page 23, lines 4-6).

Claim 4, which also depends from claim 1, specifies that the acceptor doping layer exhibits a p-type conductivity as grown. (*see e.g.*, page 31, lines 1-6).

Claim 6, which depends from claim 1, and claim 18, which depends from claim 17, specify that "the active layer has a quantum well structure, and the active layer has an averaged surface roughness which is equal to or less than a thickness of a well layer in the quantum well structure." (*see e.g.*, page 36, lines 3-7, paragraph 80).

Claim 7, which depends from claim 1, specifies that "the active layer includes at least one well layer and at least one barrier layer." (*see e.g.*, page 41, lines 13-19).

Claim 12, which depends from claim 1, specifies that the "active layer is formed evenly with respect to a macroscopic view and a microscopic view relating to an order of thickness of the active layer." (*see e.g.*, Figure 10, page 39, lines 16-24, paragraph 85).

Claim 13, which depends from claim 1, specifies that the "acceptor doping layer is formed evenly with respect to a macroscopic view and a microscopic view relating to an order of thickness of the active layer." (*see e.g.*, Figure 10, page 39, lines 16-24, paragraph 85).

Claim 17, which depends from claim 14, recites that "the GaN substrate and the active layer are formed so as to be apart from each other by a distance which is equal to or greater than about 1 μm." (*see e.g.*, page 39, lines 16-22; paragraph 85).

Claim 19, which depends from claim 14, recites that "the acceptor doping layer has a hole density of 10^{17} cm^{-3} or more. (*see e.g.*, page 59, lines 5-9; paragraph 123; page 35 line 14 – page 36 line 3, paragraphs 79-80).

VI. GROUNDS OF REJECTION TO BE REVIEWED ON APPEAL

Claims 1, 3-4, 6-7, and 12-15, and 17-19 ("rejected claims") have been rejected under 35 U.S.C. §103(a) as allegedly being unpatentable over Kimura et al. (6,201,823), in combination with Zauner et al, Mat. Res. Soc. Symp. Vol 595 (2000), herein referred to as "Zauner."

VII. ARGUMENTS

A. The Zauner article is not available prior art against the rejected claims, and therefore this rejection is inappropriate and must be withdrawn.

Zauner was made available to the public on the World Wide Web for the first time on or about May 17, 2000 through publication in the electronic journal cited above. (*see* e-mail by Eric Hellman in the Evidence Appendix). There is no evidence cited by the Examiner showing that the first availability of this article to the public was materially earlier than May 17, 2000. Thus, in the absence of any countervailing evidence, the publication date of the Zauner article must be considered to be on or about May 17, 2000. (*see* Ex parte Albert, 18 USPQ2d 1325 (Bd. Pat. App. & Interferences 1984) (deciding on a publication date based on nominal publication date, absent additional evidence).

Based on the foreign priority application date, the benefited priority date for the above-listed claims is January 12, 2000. Because the priority date from which these claims benefit is prior to the established publication date of Zauner, Zauner is not prior art against the rejected claims, and this rejection is inappropriate and must be withdrawn.

Nevertheless, the remainder of this appeal brief assumes that Zauner is available prior art, and proves that the proposed combination of Kimura and Zauner is insufficient to render any of the rejected claims obvious. Certainly, if the proposed combination of Kimura and Zauner is insufficient for purposes of 35 U.S.C. 103, then the Zauner Abstract, which is apparently prior art, in combination with Kimura is also insufficient. Both Zauner and the Zauner Abstract are included in the Evidence Appendix.

B. The Examiner has failed to prove a *prima facie* case of obviousness in the proposed combination of Kimura and either Zauner or the Zauner Abstract because these references do not disclose "a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle..."

To arrive at the argument that Zauner teaches the above-recited limitation, the Examiner stated that, "Zauner particularly teaches obtaining smoother layers due to suppression of...hexagonal pyramids of GaN growth...with off-angle orientation from <000-1> direction or <u>inherently</u><0001> [sic] direction." (Paper No. 20050316, page 3, first complete paragraph, emphasis added). Before reliance on inherency for meeting any portion of a claim limitation, the Examiner "must provide a basis in fact and/or technical reasoning to reasonably support the determination that...the characteristic <u>necessarily</u> flows from the teachings of the applied prior art." Ex parte Levy 17 USPQ2d 1461, 1464 (Bd. Pat. App. & Interferences 1990); MPEP 2112. The Examiner has provided no proper basis for asserting that a teaching of Zauner relating to tilting of a (000-1) N-side substrate by between 0-4° to reduce macroscopically large (10-50μm) hillock growth is applicable to a (0001) Ga side substrate. There are well-known and acknowledged differences between (0001) and (000-1) substrates in GaN that prevent use of inherency here, including the recognition in Zauner itself that (0001) substrates are not as susceptible to hexagonal hillock growths, "GaN growth...on the so-called Ga-side, can lead to smooth and transparent films." (Zauner Abstract, first sentence). Zauner also plainly states, "the surface morphology of GaN layers depends significantly on the polarity of the layers" (Zauner Abstract, first sentence). Therefore, reliance on inherency to extrapolate a teaching relating to (000-1) substrates into a teaching relating to (0001) substrates is inappropriate.

As an alternative to inherent disclosure, the Examiner appears to have argued that Zauner explicitly teaches tilting (0001) plane substrates. For example, the Examiner stated, "Zauner et al presents the results GaN grown on GaN substrate off-oriented with GaN grown on GaN substrate with <0001> orientation (table. 1).") (Paper No. 20050316, page 3) More accurately, Table I, like the rest of Zauner, describes "<u>N-side of GaN single crystals</u> with off-angle orientations of 0°, 2°, and 4° towards the [10-10] direction was used as a substrate for homo-epitaxial MOCVD growth." (Zauner, abstract, first sentence, emphasis added). Nevertheless, the Examiner alleges that, "Zauner teaches the substrate is (000-1) or (0001) plane" (*see e.g.*, Paper No. 20050316, page

3, last paragraph). Zauner does not so teach. Zauner certainly acknowledges the existence of the (0001) plane GaN, by noting that "GaN growth...on the so-called Ga-side, can lead to smooth and transparent films." (Zauner Abstract, second sentence). But Zauner does not teaching tilting the (0001) plane, since this plane does not possess the problem of interest in Zauner, which is reduction of macroscopic hillock density. Hence, Zauner shows that a 4° misorientation on the N-side of GaN single crystals resulted in "a reduction of the density of grown hillocks by almost two orders of magnitude as compared with homo-epitaxial films grown on the exact (000-1) surface" (Zauner, Abstract, first and second sentences, emphasis added).

Other passages of Zauner emphasize the fact that Zauner is concerned with (000-1) substrates. For example, "growth predominantly in the [0001] direction (N-side), the layer is tending to form hexagonal pyramids...surface morphology of homo-epitaxial GaN layers grown by low-pressure MOCVD was studied for different off-angle orientations, 2° and 4°, from the [0001] direction of GaN substrates...It was found that the formation of hexagonal pyramids on these N-side substrates could be suppressed by using a large enough misorientation." (Zauner abstract in Evidence Appendix, *emphasis added*; *see also* Abstract, Introduction, and Conclusions of Zauner).

In conclusion, there is no teaching explicitly or inherently in Zauner and/or Kimura regarding "a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle..." Therefore, the 35 U.S.C. 103 rejections against the rejected claims should be withdrawn and the rejected claims should be allowed to issue.

C. There is no sufficient motivation either provided by the Examiner, present in the references, or in the knowledge of one of ordinary skill in the art to combine Zauner with Kimura to produce a semiconductor light emitting device having all the limitations of claim 1.

As described above, Zauner is concerned with reducing the incidence of large (10-50μm) hillocks that tend to grow on the N side of GaN wafers, because it is desirable to be able to use the N side for growth. According to Zauner, the N side is desirable compared with the Ga side because it can be mechano-chemically polished to an epi-ready substrate, while the Ga side can only be mechanically polished, and then must be etched with reactive ion etching to obtain an epi-ready substrate. (Zauner, introduction, second paragraph) Zauner specifically acknowledges that such

large (10-50μm) hillocks are not a problem on the Ga side of GaN wafers (*see* Zauner Abstract, first sentence quoted above).

By important contrast, the present claims are directed to a different problem: reduced fluctuation in the thickness of device barrier layers and well layers grown in a two-dimension growth mode (*see* page 31, lines 13-15 and page 15, line 25 to page 19 line 12). The problem addressed by the present claims is a problem of microscopic smoothness, which is contrasted with the macroscopic smoothness problem of Zauner. The barrier and well layers of the present claims may and often do have thicknesses smaller than 1μm, and surfaces far smoother (nm smooth) than that. For example, FIG. 7 illustrates obtaining average surface roughness below 1nm for certain tilt angles. Such an effect would not be noticeable in the system of Zauner, which is concerned with surface features at least 100 times larger than those of the present invention (10-50μm hillocks). By further example, the sum of the thickness of all the layers between the GaN substrate and the active layer may be as thin as 1μm (*see* claim 1). In the illustration of FIG. 1A, there are four layers between the substrate 101 and the active layer 106. Thus, the present inventions are concerned with uniformity on a scale much smaller than Zauner; Zauner did not provide a solution to surface uniformity on the scale of 1μm and below. For example, the best results for hillock reduction were observed at a tilt (misorientation) of 4° (*see* Zauner, Table I at page 6.3.3). However, even at a tilt of 4°, the hillock density is still $1.3 \times 10^3/cm^2$, and there was no discussion regarding reduction in hillock size. Thus, Zauner did not provide a solution to "nm scale" surface smoothness, but instead found a way to reduce density of hillocks on (000-1) planes and to explain the continued existence of hillocks even at a tilt angle of 4° (*see* discussion beginning on page 6.3.3 and proceeding to page 6.3.5).

Further evidence of a lack of motivation to combine is that aspects of the present invention include a goal of obtaining a GaN crystal having a high hole density "as grown" (*see* page 3, lines 4-5). A high hole density provides a lower contact resistance from the p-type layer to a contact, which allows a lower operational voltage for a light emitting device (*see* page 4, lines 9-16). According to FIG. 6, hole density tends to drop for a substrate tilt that is much less than 0.5° and much greater than 2°. By contrast, Zauner only teaches a continuous and gradual decrease in hillock density for a substrate tilt increasing from 0 to 2 and to 4 degrees (*see* Zauner, Table I on

page 6.3.3.). There is absolutely no hint in Kimura or Zauner regarding the effect that tilting would have on hole density, or the sensitivity to the recited tilt range of claim 1. Thus, one of skill in the art would understand Zauner as teaching that a tilt of greater than 2° is preferable to one less than 2°, because of further hillock density reduction.

Respectfully, the Examiner's argument that Zauner teaches "as the tilt angle increases from 0 to 2 to 4 degrees the hillock density decreases in graduation...[h]ence, it would have been obvious to one of ordinary skill in the art to see reduction in hillock density from 0 to 4 degrees, including instant claimed range, in graduation" only proves the point that Zauner does not disclose the criticality of the claimed range for the purposes of device functionality (Paper No. 20050316, page 4, end of continued paragraph; *see also* page 5, first continued paragraph).

In sum, the Examiner has argued that a GaN (0001) plane inherently has the same characteristics and problems as a (000-1) GaN plane, and that a teaching relating to tilting, by up to 4 degrees, of a (000-1) GaN plane for the purpose of reducing 10-50μm hillock density, discloses a "GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is less than 2°." Such an argument contradicts Zauner itself by attempting to solve a problem that Zauner teaches does not exist in the (0001) plane. Further, Zauner teaches that 4 degrees of tilt is superior to 2, which further illustrates that Zauner is directed to solving a different problem than the present inventions, which one of ordinary skill in the art would recognize.

Thus, one of skill in the art would not be motivated to (1) to adapt the (000-1) plane tilt of Zauner for use with (0001) planes, (2) further modify Zauner to select the particular tilt range of "equal to or greater than 0.05° and which is less than 2°" from the 0-4° range of Zauner, (3) combine modified Zauner with Kimura to produce a device having a "GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is less than 2°." Therefore, the 35 U.S.C. 103 rejections are inappropriate and should be withdrawn.

D. There is no reasonable expectation of success in combining Zauner with Kimura to arrive at a light emitting device with all the limitations of claims 12, 13, 18, and 19.

First, the Examiner apparently agrees that Kimura does not disclose use of either a (0001) or (000-1) plane GaN single crystal in a light emitting device. (*see* Paper No. 20050316, page 2 last sentence to first sentence on page 3). Zauner, in turn, describes experiments involving, "N-side of GaN single crystals with off-angle orientations...used as substrate for homo-epitaxial MOCVD growth." (Zauner, abstract, first sentence). Respectfully, the Examiner summarily concluded that "it would have been obvious to replace sapphire substrate with GaN substrate...for the benefit of obtaining smoother layers with less density of grown hillocks..." (Paper No. 20050316, page 3, second full paragraph). However, if this is what "success" is expected by combining Zauner and Kimura, the Examiner has identified a goal that Zauner teaches is not relevant to (0001) substrates as hillock growth on (0001) plane substrates is not apparently a problem (*see* Zauner Abstract). Neither Zauner or Kimura deal with smoothness on the scale of nanometers, as discussed above, and therefore there could be no reasonable expectation to achieve nanometer smoothness based on Zauner or Kimura. At the most, the Examiner appears to be advancing an "obvious to try" rationale that someone would want to try tilting (0001) planes because Zauner describes a benefit to tilting (000-1) planes. This argument, aside from reliance on impermissible hindsight (In re Fine, 5 USPQ2d 1596, 1598 (Fed. Cir. 1988); In re Geiger, 2 USPQ2d 1276, 1278 (Fed. Cir. 1987)) ignores the fact that Zauner teaches its solution is not needed in (0001) planes, and also ignores the criticality of the tilt angle range claimed.

E. The alleged *prima facie* obviousness of the recited range of tilt angles, "equal to or greater than 0.05° and which is less than 2°" is rebutted by the demonstrated criticality of this range, which is in no way comprehendible from the teachings of Kimura or Zauner.

Admittedly, Zauner discloses tilting (000-1) plane GaN substrates at 0°, 2°, and 4°. As such, there is an argument that Zauner discloses tilting (000-1) substrates within the range of 0-4°. If that argument is accepted, then it would appear that the claimed subrange of "equal to or greater than 0.05° and which is less than 2°" is prima facie obvious over Zauner. *See* MPEP 2144.05. Nevertheless, the claimed range has a criticality to the present invention which is not derivable from any reference cited by the Examiner. For one thing, FIG. 6 illustrates that hole density is strongly dependent on tilt angle, in a way that would not be apparent from Zauner or Kimura. FIG. 6 shows

that at a tilt angle decreasing from 0.5° to 0° hole density decreases by orders of magnitude. A similar pattern is observed for tilt ranges greater than 2°, as illustrated by FIG. 6. One of skill in the art would not have perceived that hole density was so sensitive this range of tilt angles based on Kimura and Zauner, given that the matter was not even discussed in either reference. The Examiner noting that Zauner teaches hillock density monotonically decreases "in gradation" as the tilt angle is increased from 0° to 4° is certainly insufficient to teach the criticality of the claimed subrange. In fact, this observation is direct evidence that one of ordinary skill in the art would <u>not</u> be motivated to select this subrange based on the art cited by the Examiner (Paper No. 20050316, page 4, last two sentences).

Also, FIG. 7 of the present application illustrates that the dislocation density (e.g., screw dislocations) in the grown GaN rises around 2°. Here again, the Examiner has recognized the "in gradation" relationship in Zauner between hillock density and increasing tilt angles from 0° to 4°. Such results in Zauner could not plausibly be said to disclose or suggest the relationship of tilt and dislocation density in (0001) GaN planes presented in FIG. 7. Rather than a monotonic decrease in dislocation density from 0° to 4°, there is a spike in dislocations at around 2°.

Such results overwhelmingly illustrate the significance of the recited tilt angle range. These results thus also demonstrate that the recited tilt angle range is not rendered obvious by the 0° to 4° range taught by Zauner for reducing "in graduation" (000-1) plane large hillock density.

F. The teachings of Ishida, et al. (6,815,726) ("Ishida"), although not applied in any formal rejection of the claims by the Examiner, do not cure the above-identified deficiencies in Kimura and Zauner.

The Examiner alleges "both instant invention(fig.2 and fig3) and Ishida et al fig.8) for stepped surface of GaN substrate and growing GaN on stepped surface of GaN substrate." (Paper No. 20050810, Continuation Sheet (PTO-303), last sentence, all errors in original). From what can be gleaned from the above statement, and extrapolating somewhat to make sense of it, it appears that the Examiner is arguing that the steps of Ishida, disclosed for example as stepped portion 500a in FIG. 8, teach tilting of GaN (0001) planes as recited in Claim 1, e.g. The Examiner appears to

find support from FIG. 3 of the present application, as it illustrates steps. Respectfully, the Examiner has misapprehended the relevance of FIG. 3. As described on page 16, lines 4 to page 17 line 1, the steps 302 on the substrate 301 are distributed in an "optimum" manner, resulting in "two-dimensional growth." However, "during the growth process, the steps from which the two-dimensional growth began will gradually disappear, ultimately attaining a very flat uppermost surface." In other words, during the growth of GaN on the slightly tilted (0001) GaN surface, two dimensional growth first begins at those steps, but ends with a very flat top surface. Ishida, with its various examples, discloses <u>device cross-sections</u> where the <u>finished device</u> has a layer with some sort of step that according to Ishida reduces dislocations near the step.

Neither can Ishida be relied upon for the more general proposition that a (0001) plane is functionally equivalent to a (000-1) plane, as nowhere does Ishida teach anything remotely to that effect. Moreover, every example of Ishida apparently discloses using (0001) plane GaN substrates. Tellingly, Ishida does not indicate that a (000-1) plane is substitutable in such examples. Ishida does not disclose tilting a substrate in any orientation, let alone the range recited in claim 1. Therefore, Ishida does not help make the case for equivalence of (0001) and (000-1) substrates, and Ishida can be of no help in curing the defects described above in Kimura and Zauner. If anything, the teachings of Zauner and Ishida mitigate towards the patentability of the rejected claims, as they support the difference between (0001) and (000-1) planes.

G. Conclusion

Evidence in the record is that Zauner teaches (1) homo-epitaxial growth on N-side GaN substrates leads to formation of hexagonal pyramids, (2) homo-epitaxial growth on Ga-side GaN substrates may lead to formation of "smooth and transparent films" on the larger scale that concerned Zauner, (3) N-side substrates can be mechano-chemically polished to epi-ready substrates while Ga-side substrates can only be mechanically polished and therefore require reactive ion etching to obtain epi-ready substrates, (4) "surface morphology of GaN layers depends significantly on the polarity of the layers," (5) large hillock density in (000-1) substrates decreases "in graduation" by increased tilt from 0-4°, (6) hole density drops for (0001) substrate tilts much outside the range of "equal to or greater than 0.05° and which is less than 2°," and (7) screw dislocation density increases for (0001) substrate tilts much outside the range of "equal to or greater than 0.05° and which is less than 2°."

In spite of all this evidence in the record pointing to differences between (0001) and (000-1) substrates, and the non-obviousness of the claimed range, the Examiner urges that the teachings in Zauner relating to a problem endemic to (000-1) substrates (i.e., N side planes) can be changed and extrapolated to a more specific claim recitation relating to (0001) substrates (i.e., Ga side planes) to solve a problem not even considered by Zauner. This without any consideration for the remarkable and unanticipated results of FIGS. 6 and 7, which further point out the non-obviousness of the claims over Zauner and Kimura. This 35 U.S.C. 103 rejection cannot withstand such scrutiny, and the Applicant therefore respectfully requests that the rejections be withdrawn and claims 1, 3-4, 6-7, 12-15, and 17-19 be allowed to issue.

Dated: 11/22/05

Respectfully submitted,

By [signature]

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VIII. Claims Appendix

Claims Involved in the Appeal of Application Serial No. 09/759,312

Claim 1 (previously presented): A nitride compound semiconductor light emitting device comprising:

a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is less than 2°, and

a n-type layer containing a nitride compound semiconductor located above the GaN substrate, and

an active layer containing a nitride compound semiconductor located above the GaN substrate, and

an acceptor doping layer containing a nitride compound semiconductor comprising $Ga_xIn_yAl_{1-(x+y)}N$ (where $0 \leq x \leq 1$; $0 \leq y \leq 1$; and $0 \leq x+y \leq 1$) located above the GaN substrate,

wherein the GaN substrate and the active layer are formed so as to be apart from each other by a distance which is equal to or greater than about 1μm.

Claim 2 (cancelled)

Claim 3 (original): A nitride compound semiconductor light emitting device according to claim 1, wherein the GaN substrate has a crystal orientation which is tilted away from a <0001> direction in a <11-20> or <1-100> direction.

Claim 4 (previously presented): A nitride compound semiconductor light emitting device according to claim 1, wherein the acceptor doping layer exhibits a p-type conductivity as grown.

Claim 5 (cancelled)

Claim 6 (original): A nitride compound semiconductor light emitting device according to claim 1, wherein the active layer has a quantum well structure, and the active layer has an averaged surface roughness which is equal to or less than a thickness of a well layer in the quantum well structure.

Claim 7 (original): A nitride compound semiconductor light emitting device according to claim 1, wherein the active layer includes at least one well layer and at least one barrier layer.

Claim 8 (withdrawn): A method for producing a nitride compound semiconductor light emitting device, wherein a semiconductor multilayer structure including an active layer of a quantum well structure made by a nitride compound semiconductor and an acceptor doping layer is integrated on a GaN substrate having a crystal orientation which is tilted away from a <0001> direction by an angle which is equal to or greater than about 0.05° and which is equal to or less than about 2°, the active layer including at least one barrier layer and at least one well layer, the method comprising the steps of:

stopping the growth of the active layer for a certain period of time after forming the well layer of the active layer including the at least one barrier layer and at least one well layer; and

stopping the growth of the nitride compound semiconductor for a certain period of time after forming the nitride compound semiconductor which contacts with the well layer and becomes the barrier layer having band-gap energy larger than that of the well layer.

Claim 9 (withdrawn): A method according to claim 8, wherein the predetermined length of a wait period is equal to or greater than about 1 second and is equal to or less than about 60 minutes.

Claim 10 (withdrawn): A method according to claim 8, further comprising:

supplying a carrier gas into the chamber, in which the GaN substrate is placed, during a wait period after at least one of the at least one well layer and the at least one barrier layer has been formed, the carrier gas comprising nitrogen as a main component.

Claim 11 (withdrawn): A method according to claim 8, further comprising:

supplying a carrier gas and a group V gas into a chamber, in which the GaN substrate is placed, during a wait period after at least one of the at least one well layer and the at least one barrier layer has been formed, the carrier gas comprising nitrogen as a main component.

Claim 12 (previously presented): A nitride compound semiconductor light emitting device according to claim 1, wherein said active layer is formed evenly with respect to a macroscopic view and a microscopic view relating to an order of thickness of the active layer.

Claim 13 (previously presented): A nitride compound semiconductor light emitting device according to claim 1, wherein said acceptor doping layer is formed evenly with respect to a macroscopic view and a microscopic view relating to an order of thickness of the active layer.

Claim 14 (previously presented): A nitride compound semiconductor light emitting device comprising:

a GaN substrate having a (0001) plane whose crystal orientation is tilted away from a <0001> direction by an angle which is equal to or greater than 0.05° and which is 2°, and

a n-type layer containing a nitride compound semiconductor located above the GaN substrate, and

an active layer containing a nitride compound semiconductor located above the GaN substrate, and

an acceptor doping layer containing a nitride compound semiconductor comprising $Ga_xIn_yAl_{1-(x+y)}N$ (where $0 \leq x \leq 1$; $0 \leq y \leq 1$; and $0 \leq x+y \leq 1$) located above the GaN substrate, wherein the acceptor doping layer exhibits a p-type conductivity as grown.

Claim 15 (previously presented): A nitride compound semiconductor light emitting device according to claim 14, wherein the GaN substrate has a crystal orientation which is tilted away from a <0001> direction in a <11-20> or <1-100> direction.

Claim 16 (cancelled)

Claim 17 (previously presented): A nitride compound semiconductor light emitting device according to claim 14, wherein the GaN substrate and the active layer are formed so as to be apart from each other by a distance which is equal to or greater than about 1 μm.

Claim 18 (previously presented): A nitride compound semiconductor light emitting device according to claim 17, wherein the active layer has a quantum well structure, and the active layer has an averaged surface roughness which is equal to or less than a thickness of a well layer in the quantum well structure.

Claim 19 (previously presented): A nitride compound semiconductor light emitting device according to claim 14, wherein the acceptor doping layer has a hole density of 10^{17} cm^{-3} or more.

IX. Evidence Appendix

This Appendix contains the following items, which were entered into the record as described.

A. The Zauner Abstract was an abstract of a lecture expected to be presented by Zauner at "Symposium W GaN and Related Alloys," which occurred from November 28 – December 3, 1999. This abstract was submitted for consideration by the Examiner in an information disclosure statement included with the July 25, 2005 response to the then-final office action dated March 29, 2005 (Paper No. 20050316).

B. Zauner, A.R.A., et al., "Homo-epitaxial growth on misoriented GaN substrates by MOCVD," (published online by the Materials Research Society on or about May 17, 2000). There may have been a printed proceedings volume available before that date. Zauner was cited by the Examiner in a rejection dated 11/1/2002.

C. Kimura, "Gallium Nitride Based Compound Semiconductor Laser and Method of Forming the Same" (6,201,823). This patent was cited by the Examiner as part of a rejection made in March of 2002.

D. Ishida, "Semiconductor Device and Semiconductor Substrate and Method of Fabricating Same" (6,815,726). Ishida was cited in a Continuation Sheet included with an advisory action mailed 8/16/2005.

E. E-mail from Eric Hellman relating to the publication date of Zauner. This e-mail was submitted for consideration by the Examiner on July 25, 2005, in response to the then-final office action dated March 29, 2005 (Paper No. 20050316).

X. Related Proceedings Appendix

There are no related proceedings which will directly affect or be directly affected by or have a bearing on the Board's decision in this appeal.

PTO/SB/17 (12-04v2)
Approved for use through 7/31/2006. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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FEE TRANSMITTAL
For FY 2005

☐ Applicant claims small entity status. See 37 CFR 1.27

TOTAL AMOUNT OF PAYMENT ($) 500.00

Complete if Known	
Application Number	09/759,312
Filing Date	January 12, 2001
First Named Inventor	Yoshihiro UETA
Examiner Name	S. Mulpuri
Art Unit	2812
Attorney Docket No.	299002051800

METHOD OF PAYMENT (check all that apply)

☐ Check ☐ Credit Card ☐ Money Order ☐ None ☐ Other (please identify): ____

☒ Deposit Account Deposit Account Number: 03-1952 Deposit Account Name: Morrison & Foerster LLP

For the above-identified deposit account, the Director is hereby authorized to: (check all that apply)

☒ Charge fee(s) indicated below
☐ Charge fee(s) indicated below, **except for the filing fee**
☒ Charge any additional fee(s) or underpayment of fee(s) under 37 CFR 1.16 and 1.17
☒ Credit any overpayments

FEE CALCULATION

1. BASIC FILING, SEARCH, AND EXAMINATION FEES

	FILING FEES		SEARCH FEES		EXAMINATION FEES		
Application Type	**Fee ($)**	**Small Entity Fee ($)**	**Fee ($)**	**Small Entity Fee ($)**	**Fee ($)**	**Small Entity Fee ($)**	**Fees Paid ($)**
Utility	300	150	500	250	200	100	
Design	200	100	100	50	130	65	
Plant	200	100	300	150	160	80	
Reissue	300	150	500	250	600	300	
Provisional	200	100	0	0	0	0	

2. EXCESS CLAIM FEES

Fee Description	**Fee ($)**	**Small Entity Fee ($)**
Each claim over 20 (including Reissues)	50	25
Each independent claim over 3 (including Reissues)	200	100
Multiple dependent claims	360	180

Total Claims		**Extra Claims**		**Fee ($)**		**Fee Paid ($)**
16	- 20 =	0	x	50.00	=	0.00
Indep. Claims		**Extra Claims**		**Fee ($)**		**Fee Paid ($)**
3	- 3 =	0	x	200.00	=	0.00

Multiple Dependent Claims

Fee ($)	**Fee Paid ($)**
360.00	0.00

3. APPLICATION SIZE FEE

If the specification and drawings exceed 100 sheets of paper (excluding electronically filed sequence or computer listings under 37 CFR 1.52(e)), the application size fee due is $250 ($125 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).

Total Sheets ____ - 100 = **Extra Sheets** ____ /50 **Number of each additional 50 or fraction thereof** ____ (round up to a whole number) x **Fee ($)** ____ = **Fee Paid ($)** ____

4. OTHER FEE(S) **Fees Paid ($)**

Non-English Specification, $130 fee (no small entity discount)

Other (e.g., late filing surcharge): 1402 Filing a brief in support of an appeal 500.00

SUBMITTED BY					
Signature	Michael S. Garrabrants	Registration No. (Attorney/Agent)	51,230	Telephone	(650) 813-4227
Name (Print/Type)	Michael S. Garrabrants			Date	November 22, 2005

SYMPOSIUM W

GaN and Related Alloys

November 28 December 3, 1999

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Proceedings published as Volume 595 of the Materials Research Society Symposium Proceedings Series.

* Invited paper

layers. To determine the crystal quality and the stress in the layers High Resolution XRD measurements were performed.

4:45 PM W5.10
PROBING NITRIDE THIN FILMS IN 3-DIMENSIONS USING A VARIABLE ENERGY ELECTRON BEAM. C. Trager-Cowan, P.G. Middleton, A. Mohammed, S.K. Manson-Smith, I. Osborne, M. Barisonzi and K.P. O'Donnell., Strathclyde Univ, Dept. Physics and Applied Physics, Glasgow, SCOTLAND; W. Van der Stricht, K. Jacobs, I. Moerman and P. Demeester, IMEC-INTEC, University of Gent, Gent, BELGIUM; M.F. Wu and A. Vantomme, KU Leuven, Leuven, BELGIUM.

Thin films incorporating GaN, InGaN and AlGaN are presently arousing considerable excitement because of their suitability for UV and visible light emitting diodes and laser diodes. However, because of the lattice mismatch between presently used substrates and epitaxial nitride thin films, the films are of variable quality. We are presently using a number of novel techniques in the scanning electron microscope, namely cathodoluminescence (CL) imaging, CL spectroscopy and electron backscattered diffraction (EBSD), to investigate both the structural and optical properties of such films in 3-dimensions. Information in the 3rd dimension is extracted by acquiring data at different electron beam energies. We are using these techniques to 1) map and depth profile strain in the films, where the strain is due to the lattice mismatch mentioned earlier; 2) map and depth profile defect distributions; 3) investigate zinc blende inclusions in thin films of predominantly wurtzite material, and 4) map and depth profile the variation in alloy composition in alloy films. Results to date include (i) the acquisition of CL images of an InGaN/GaN multiple quantum well (MQW) grown on an epitaxially lateral overgrown GaN (ELOG) layer. We have shown that the luminescence efficiency of both the GaN and the MQW is improved for material lying above the stripes of the SiO_2 mask compared to that above the windows of the mask or unpatterned material; (ii) the depth profiling of the indium mole fraction of a 0.4 mm InGaN epilayer using CL spectroscopy. The CL peak was found to shift from $\approx$ 2.80 to $\approx$ 2.85 eV, which shows that the In content decreases with increasing depth; (iii) the acquisition of EBSD patterns from GaN epilayers. EBSD allows the comparison of the crystalline quality of epilayers grown under different growth conditions.

SESSION W6: GROWTH MOCVD, HVPE, BULK
Chair: Hiroshi Amano
Wednesday Morning, December 1, 1999
Room 302 (H)

8:30 AM *W6.1
COMPARISON OF InGaN LAYERS GROWN ON BULK GaN AND SAPPHIRE SUBSTRATES. Shiro Sakai, Tokushima University, Dept of Electrical and Electronic Engineering, Minami-josanjima, Tokushima, JAPAN.

InGaN/GaN SQW(Single Quantum Well) and MQW (Multiple Quantum Well) were grown on sapphire and bulk GaN substrates and compared. A bulk GaN substrate was either a free-standing bulk GaN crystal prepared by the sublimation method or a thick GaN film prepared by the direct synthesis of Ga metal and ammonia on MOCVD-grown GaN/sapphire substrate. Both crystals had high crystal perfection with low dislocation density. SQW and MQW grown on these substrates were characterized by TEM , CL and PL. A clear phase separation in sub-micron-range-domains with different indium composition was observed in thick-InGaN films grown at relatively low temperature on sapphire substrates but not on bulk GaN. Although such a phase separation was not seen in thin-InGaN grown at higher temperature, abnormal temperature behavior of PL peak wavelength, which was attributed to the existence of the band tail was observed in all InGaN layers grown on sapphire. The band tail became large with increasing indium composition. These results indicate that a dislocation plays a key role in the phase separation and compositional fluctuation in InGaN films. The behavior of dislocation-free-InGaN grown on GaN substrate is quite normal.

9:00 AM *W6.2
OMVPE Growth of (Al,Ga,In)N for UV Optoelectronics. Jung Han and M.H. Crawford, Sandia National Laboratories, Albuquerque, NM.

Nitride-based ultraviolet (UV) light source is attractive for applications such as energy-efficient indoor lighting and various forms of chemical sensing. The development of UV emitters, however, faces challenges in both device design and material growth. Issues unique to the growth of nitride-based UV emitters, specifically the control of structural coherency and the enhancement of optical efficiency, are discussed in this work. It is shown that the common configuration of nitride-based visible-light emitters, based on the growth of ternary (AlGaN and GaInN) heterostructures on thick binary GaN buffers, imposes stringent constraints to the implementation of UV emitters; the demand of a higher barrier with AlGaN implies an increased tensile mismatch to GaN. Two approaches to circumvent this issue will be discussed in this paper: i) the use of a thick AlGaN ternary buffer and ii) the employment of quaternary AlGaInN as wider bandgap nitrides lattice-matched to GaN. The viability of the employment of binary GaN as an active layer for UV emitters was also studied. Improvement of optical efficiency was achieved by optimizing the growth condition of GaN and the introduction of indium. Sandia is a multiprogram laboratory, operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy, under contract DE-AC04-94AL85000.

9:30 AM W6.3
HOMOEPITAXIAL GROWTH ON MISORIENTED GaN SUBSTRATES BY MOCVD. A.R.A. Zauner, J.L. Weyher, V. Kirilyuk, P.R. Hageman, and P.K. Larsen, Dept. Experimental Solid State Physics III, Research Institute for Materials, University of Nijmegen, THE NETHERLANDS; S. Porowski, High Pressure Research Center, Polish Academy of Science, Warsaw, POLAND.

The surface morphology of GaN layers depends significantly on the polarity of the layers. GaN growth in the [0001] direction, or on the so-called Ga-side, can lead to smooth and transparent films. For growth predominantly in the [0001] direction (N-side), the layer is tending to form hexagonal pyramids. The main advantage for growth on the N-side of GaN bulk crystals is the fact that this side can be mechano-chemically polished to obtain epi-ready substrates for homo-epitaxial growth, this is in contrast with the Ga-side that can only be mechanically polished. For device applications, formation of hexagons on top of the surface should be avoided. A common way to avoid growth features on top of the surface is the use of misoriented substrates. In the present work the surface morphology of homo-epitaxial GaN layers grown by low-pressure MOCVD was studied for different off-angle orientations, 2° and 4°, from the [$\bar{0}$001] direction of GaN substrates. It was found that the formation of hexagonal pyramids on these N-side substrates could be suppressed by using a large enough misorientation. Optical differential interference contrast microscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM) were used to investigate the morphology of the layers. The optical quality, provided by photoluminescence (PL) measurements, is in the order of 1 meV as expected for homo-epitaxial growth.

9:45 AM W6.4
CRITICAL LAYER THICKNESS OF GaN/$In_xGa_{(1-x)}N$ SYSTEM. C.A. Parker, M.J. Reed[1], J.C. Roberts, S.X. Liu[1], N.A. El-Masry[1], and S.M. Bedair Dept of Electrical and Computer Engineering, NC State Univ, Raleigh, NC; [1]Dept of Materials Science and Engineering, NC State Univ, Raleigh, NC.

Much effort has been directed towards the use of $In_xGa_{(1-x)}N$/GaN heterostructures for device applications where the strained $In_xGa_{(1-x)}N$ layers were kept well below the so called critical layer thickness (CLT). No definite information is available about the value of the critical layer thickness of $In_xGa_{(1-x)}N$ heterostructures or double heterostructures (DH) on thick GaN. We present an approach to determine the critical layer thickness of $In_xGa_{(1-x)}$/GaN heterostructures grown by atmospheric MOCVD. The $In_xGa_{(1-x)}$ films investigated have values of x between 0 and 0.20 as determined by x-ray diffraction and thickness of up to 1 μm determined by cross-sectional TEM, SEM, and depth profiling capacitance-voltage measurements (CV). Photoluminescence (PL) is employed to determine the optical emission characteristics of the films. CLT was determined by monitoring the evolution of PL emission, carrier concentration, and film resistivity as the $In_xGa_{(1-x)}$ film thickness is increased. As the $In_xGa_{(1-x)}$ film thickness increases, the onset of relaxation occurs. A red shift in band edge emission, the appearance of deep level emission, a transition to three-dimensional growth, an increase in film resistivity, and a decrease in free carriers accompany this relaxation. The CLT is deduced from the PL data by two different approaches: 1.) The CLT is considered to be the thickness at which the bandgap of strained films equals that of relaxed films, or 2.) The onset of deep level emission, assumed to arise from structural defects at the $In_xGa_{(1-x)}$/GaN interface, occurs when the film thickness exceeds the CLT. Both approaches give equivalent critical thickness values for the InGaN films and are confirmed by electrical measurements of the samples. The critical layer thickness estimates determined in this fashion are consistent with off-axis x-ray diffraction data and SEM observations of surface morphology. It should be noted that our estimates of CLT in the $In_xGa_{(1-x)}$/GaN system are larger than those previously reported for other semiconductors. We will discuss the nature of the relaxation process in $In_xGa_{(1-x)}$ heterostructures and DHs and report the CLT of the $In_xGa_{(1-x)}$ as a part of these structures. Additionally, we will discuss the effect of InGaN thickness on the electrical properties of the InGaN/GaN structure.

Mat. Res. Soc. Symp. Proc. Vol. 595 © 2000 Materials Research Society

D2

Homo-epitaxial growth on misoriented GaN substrates by MOCVD

A.R.A. Zauner[1], J.J. Schermer[1], W.J.P. van Enckevort[1], V. Kirilyuk[1], J.L. Weyher[1,2], I. Grzegory[2], P.R. Hageman[1], and P.K. Larsen[1]

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ABSTRACT

The N-side of GaN single crystals with off-angle orientations of 0°, 2°, and 4° towards the $[10\bar{1}0]$ direction was used as a substrate for homo-epitaxial MOCVD growth. The highest misorientation resulted in a reduction of the density of grown hillocks by almost two orders of magnitude as compared with homo-epitaxial films grown on the exact $(000\bar{1})$ surface. The features still found on the 4° misoriented sample after growth can be explained by a model involving the interaction of steps, introduced by the misorientation and the hexagonal hillocks during the growth process.

INTRODUCTION

Metalorganic Chemical Vapour Deposition (MOCVD) growth of Gallium Nitride (GaN) in the $[000\bar{1}]$ direction is associated with the formation of surface defects, such as hexagonal hillocks [1,2,3]. The inversion domain, located at the centre of the point-topped pyramids, apparently causes hillock formation as a result of the higher growth rate of this defect compared with the growth rate of the surrounding matrix [3]. Also for homo-epitaxial growth on the N-side of GaN substrates formation of hexagonal pyramids is observed [4,5].

Homo-epitaxial growth in the $[000\bar{1}]$ direction has the advantage that the N-side of GaN single crystals can be mechano-chemically polished to obtain epi-ready substrates [6], while the Ga-side (for growth in the [0001] direction) can only be mechanically polished, so that reactive ion etching is needed to prepare epi-ready substrates [7].

For device applications smooth surfaces are required, therefore the formation of hillocks should be avoided. A common way to avoid growth features on the surface is the use of misoriented substrates [8]. In the present work the surface morphology of homo-epitaxial GaN layers is studied for different off-angle orientations from the exact $[000\bar{1}]$ direction. It is found that the formation of hexagonal pyramids can be strongly suppressed by the use of a sufficiently large misorientation, resulting in much smoother layers.

EXPERIMENTAL

GaN single crystals [9] were used as substrates for MOCVD growth. The $(000\bar{1})$ substrate surfaces were mechano-chemically polished [6] to obtain off-angle orientations

of 0°, 2°, and 4° towards the [10$\bar{1}$0] direction. The misorientation was confirmed by X-ray diffraction analysis.

Homo-epitaxial GaN growth was performed at a temperature of 1040°C and a pressure of 50 mbar using trimethylgallium (TMG) and ammonia (NH_3) as precursors, and hydrogen (H_2) as carrier gas. The substrate crystals were heated to growth temperature under a NH_3 gas flow diluted in nitrogen (N_2). Growth was performed with a V/III molar ratio of about 1700 with a total flow of about 5 slm.

The surfaces of the homo-epitaxial GaN layers were investigated by optical differential interference contrast microscopy (DICM), a technique very sensitive for detecting local differences in surface slope, which are visualised by different shades of grey in the figures.

RESULTS AND DISCUSSION

Optical examination with DICM of layers grown on (000$\bar{1}$) substrates without misorientation reveals a large number of hexagonal growth hillocks covering almost the entire surface. As shown in figure 1a the hexagonal base of the hillocks is 10-50 μm in size. The majority of the hillocks are regular point-topped pyramids, although some of them are macroscopically flat-topped or disrupted. The highest hillocks, with steeper side facets, show an increased contrast. Similar hillock morphology has been observed for hetero-epitaxial GaN layers grown in the [000$\bar{1}$] direction [3,10]. Faster growing inversion domains of Ga-polarity in a matrix of N-polarity lead to the formation of hillocks [3]. Also for homo-epitaxial growth on the N-side hexagonal pyramids were observed [4,5].

The virtual (000$\bar{1}$) plane, of macroscopically flat-topped pyramids, is faceted due to steps generated by a step source located at the centre of the hexagon. These steps originate from dislocations at the centre of such hillocks, as was concluded from the occurrence of interlaced spirals with atomic height steps [11].

For the sample with a 2° off-angle orientation towards the [10$\bar{1}$0] direction the density of hillocks at the surface is significantly lower compared to the exactly oriented samples (see table I). The misorientation induced step flow started to overgrow part of

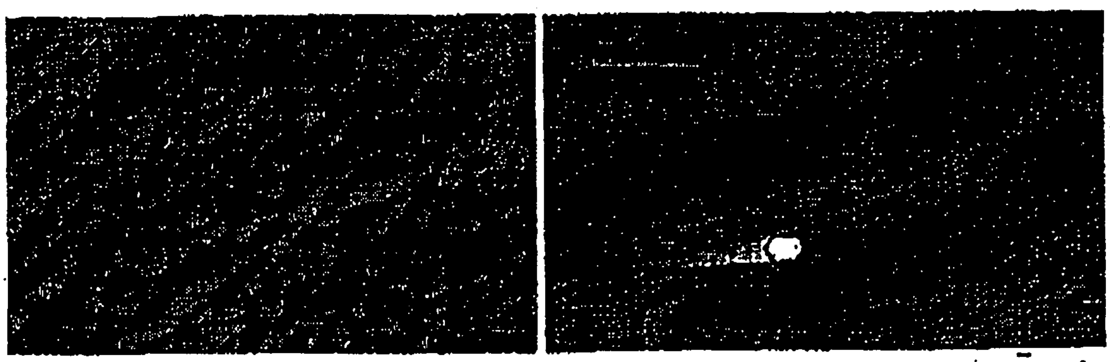

Figure 1. *DICM image of a homo-epitaxial GaN layer grown on the N-side (000$\bar{1}$) of a GaN single crystal (a) without misorientation and (b) 4° misorientation towards the [10$\bar{1}$0] direction.*

Table I. *The dependence of the hillock density on the misorientation of the GaN substrates.*

misorientation (°)	hillock density (cm^{-2})
0	1.2E+05
2	2.8E+04
4	1.3E+03

the hexagons. However, for the majority of the features on the surface the source of growth is still present. The step flow resulting from the 2° misorientation appeared to be insufficient to overgrow the centres of the hillocks.

The estimated hillock density for the 4° misoriented specimen is nearly two orders of magnitude lower as compared with specimens of exact orientation (see table I). Obviously the step flow resulting from the misorientation, which is doubled compared to the 2° off-angle sample discussed above, is sufficient to overgrow the centres of the majority of the hexagons.

Although, for 4° misorientation most hexagonal features disappeared from the surface (figure 1b), there is still a number of partial and complete hexagonal hillocks that can be recognised. A number of these features is shown in figure 2. Figure 2a shows a kind of plateau with a partly overgrown hexagonal hillock near its centre, dividing the plateau in two parts. The two regions, which border on the edges of the hillock, are not equally sized. From the difference in size of those two areas it can be concluded that the misorientation is not exactly in the [10$\bar{1}$0] direction. The plateau ends abruptly in a steep step bunch perpendicular to the [10$\bar{1}$0] direction. In figure 2b a part of a hexagon can still be recognised. Like the hillock shown in figure 2a. the two side areas that border on the hexagon are not equal in size and the plateau terminates in the [10$\bar{1}$0] direction resulting in a sharp, steep edge. For the feature shown in figure 2c a discontinuity in slope of the plateau itself can be recognised at the place where the plateau starts to narrow. On the plateaus of the surface features of figure 2a-2c steps sloping towards the <11$\bar{2}$0> directions can be seen.

A plausible explanation for the occurrence of the surface features shown in figure 2

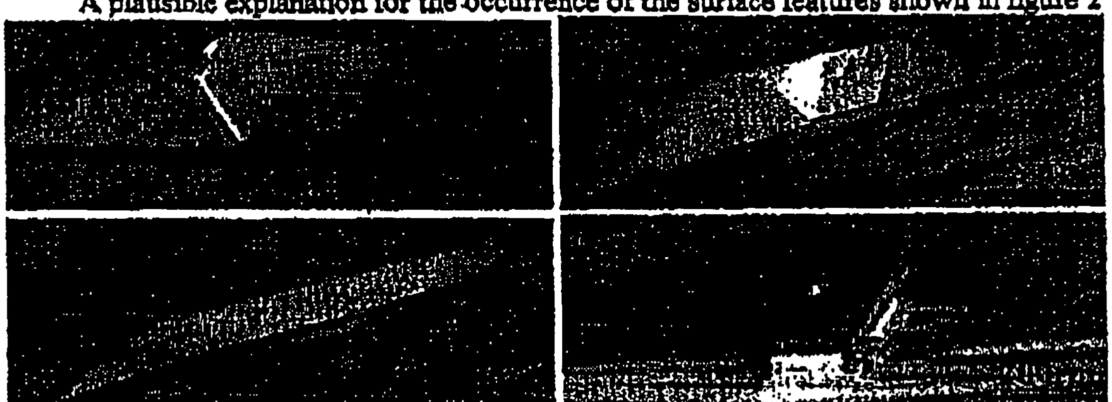

Figure 2. *DICM images of different surface features found after growth on the 4° misoriented single crystal. The arrow in c) indicates the discontinuity line on the plateaus. d)The feature indicates a fluctuation in activity of the growth centre during growth.*

can be given. The sample was mechano-chemically polished to a 4° misorientation, thereby introducing steps approximately parallel to [1 1 2 0], over the sample. At the beginning of growth shallow as well as steep hexagonal hillocks tend to be formed. However, only steep hexagonal hillocks, which are formed by a more active step source, survive the propagation of the misorientation step train and will be present after a certain period of growth (see figure 2). Less steep hillocks are overgrown in an early stage of the process or cannot be formed at all. In figure 1a it can be seen that the height of the hillocks varies over the sample. About 3% of the hillocks presented in figure 1a show an enhanced contrast which indicates steeper hillocks. This percentage is in agreement with the previous observation of the reduced hillock density by almost two orders of magnitude for the 4° misoriented sample as compared with the samples without misorientation.

In addition, the activity of many individual hillocks decreases or fluctuates during growth (see figure 2d). If the activity of the step source at the hillock centre decreases vertical growth slows down but the base of the hillock still expands. The time dependent overgrowth of a steep hillock of which the vertical growth is suddenly almost stopped is represented schematically in figure 3.

In its steep period as well as in its first time of slow vertical growth the slowest advancing steps, in the <10 $\bar{1}$ 0> directions, bound the hillock (figure 3a). The steps introduced by the misorientation are more or less in the [10 $\bar{1}$ 0] direction, which means that these steps also move slowly. Steps in other directions move considerably faster. Steps from the left and right hand side of the hillock form a re-entrant corner with the steps induced by the misorientation (see figure 3). Due to an increased effective supersaturation near this region the step velocity increases and the re-entrant corner becomes rounded [12]. Now a whole range of step orientations is created, and steps in the fast moving <11 $\bar{2}$ 0> directions are selected to propagate over the plateaus.

Figure 3b represents a hillock of which the step source has already been inactive for some time at the moment that the misorientation-induced steps just start to overgrow the flat top of the hillock. The steps on the plateau, left and right from the hillock, move faster than the steps introduced by the misorientation. During continued growth the hexagon-centre will be overgrown (figure 3d-3e).

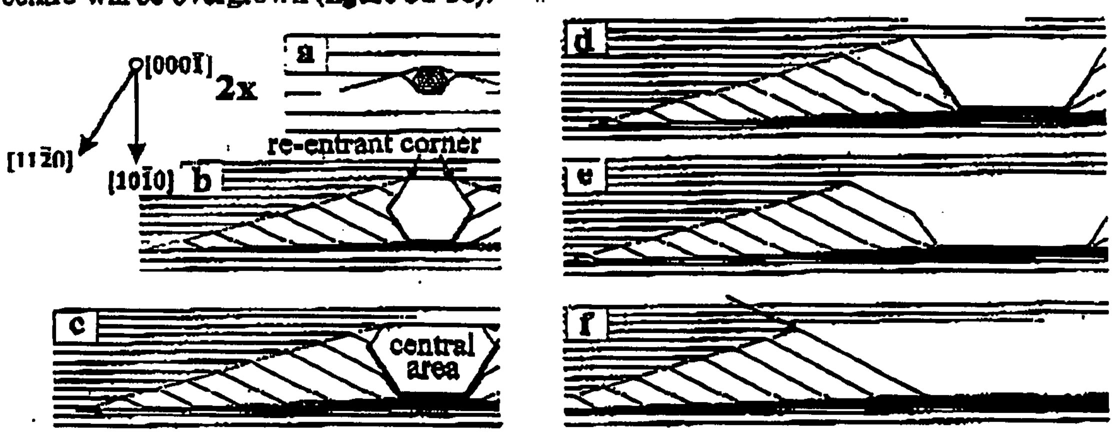

Figure 3. *Schematic representation of the time-dependent development and subsequent overgrowth of a hexagonal hillock. Image a) is two times enlarged. The arrow in f) indicates the discontinuity line on the plateau, cf. figure 2c.*

From the moment that the hillock is half overgrown, and no steps opposite to the misorientation-steps exist (figure 3d), the position of the re-entrant corner moves along the intersection line of the remaining hillock side facet and the plateau during prolonged growth (figure 3e) and will finally evanesce (figure 3f). The boundary between the stepped plateau areas and the central region of the plateau, which is more or less parallel to the $(000\bar{1})$ plane, now corresponds with the last fast $\langle 11\,20\rangle$ step emitted from the vanishing hillock, cf. figure 2c.

From the mechanism of hillock overgrowth shown in figure 3 it becomes also clear that as long as the hillock, or part of it, is present on the surface the plateaus next to the hillock become wider along $\langle 10\bar{1}0\rangle$. Since the plateaus are formed from steps emerging from the re-entrant corner, the plateaus were narrower at earlier times of growth when the hillocks were smaller. This explains the triangular shape of both plateaus parts adjacent to the hillocks and the fact that the hillock is more or less located at the centre of the plateau.

During continued growth and assuming that the steps at the steep edge of the plateau propagate as fast as the misorientation steps, the plateau expands in the left and right directions, only due to expansion of the flat central area. Apart from translation the stepped triangular plateau regions do not change in time (figure 3).

The moment at which the situation represented in figure 3b occurs during the growth process depends on the time-dependent activity of the growth source of the hillock during the earlier stage of the growth run, which is different for the individual hillocks. Therefore, different stages of feature development appear side by side on the same layer after a certain period of growth as shown in figure 2. A hillock of which the step source has become inactive at a very early stage of growth will be overgrown much faster, i.e. the time between the different stages of the overgrowth process presented in figure 3 will be much shorter. Overgrowth of the hillock will also be faster for higher misorientations towards the $[10\bar{1}0]$ direction and same step source activity of the hillock. Overgrowth of the remaining part of the hillock can only be realised if steps introduced by the misorientation move faster than the steps of the remainder of the hillock.

Steps in the $\langle 11\bar{2}0\rangle$ directions move 2.5 times as fast as steps in the $\langle 10\bar{1}0\rangle$ directions, as is determined by measuring the distances between the small step bunches on both the misoriented surface and the plateau. Therefore, a misorientation towards the $[11\bar{2}0]$ direction should be chosen in order to overgrow the surface features completely.

CONCLUSIONS

During MOCVD growth of GaN films on the N-side of exactly oriented GaN single crystal substrates, hexagonal pyramids are formed. In this study it is found that the formation of these pyramids can be largely suppressed by the use of substrates with a slight misorientation towards the $[10\bar{1}0]$ direction. For a substrate misorientation of 4° the density of the elevations on the homo-epitaxial film is reduced by almost two orders of magnitude as compared with exactly oriented GaN substrates. The morphologies of those features that persist on the 4° off-angle sample during growth can be explained by a model involving the interaction of steps introduced by the misorientation with steps originating from the hillocks.

It is found that the step velocity is dependent on the step orientation: steps in the <11$\bar{2}$0> directions move 2.5 times as fast as steps in the <10$\bar{1}$0> directions.

Considerations following from the model indicate that for a further improvement of the surface morphology by reduction of the hillock density either substrates with larger misorientations or, since the step velocity is highly anisotropic, with misorientations towards the [11$\bar{2}$0] direction are needed.

ACKNOWLEDGEMENTS

This work was financially supported by the Dutch Technology Foundation (STW). JLW wishes to thank for the grant of NATO Scientific Affair Division.

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Title: Homo - epitaxial growth on misoriented GaN substrates by MOCVD
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ISSN: 1092-5783 Publication date: 20000000
Publisher: MATERIALS RESEARCH SOCIETY, 506 KEYSTONE DR, WARRENDALE, PA 15086
Language: English Document Type: ARTICLE
Abstract: The N-side of GaN single crystals with off-angle orientations of 0 degrees, 2 degrees, and 4 degrees towards the [10 (1) over bar0] direction was used as a substrate for homo - epitaxial MOCVD growth. The highest misorientation resulted in a reduction of the density of grown hillocks by almost two orders of magnitude as compared with homo - epitaxial films grown on the exact (000 (1) over bar) surface. The features still found on the 4 degrees misoriented sample after growth can be explained by a model involving the interaction of steps, introduced by the misorientation and the hexagonal hillocks during the growth process.

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